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Basis and Methods of NASA Airborne Topographic Mapper Lidar Surveys for Coastal Studies

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ABSTRACT

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This paper provides an overview of the basic principles of airborne laser altimetry for surveys of coastal topography, and describes the methods used in the acquisition and processing of NASA Airborne Topographic Mapper (ATM) surveys that cover much of the conterminous US coastline. This form of remote sensing, also known as "topographic lidar", has undergone extremely rapid development during the last two decades, and has the potential to contribute within a wide range of coastal scientific investigations. Various airborne laser surveying (ALS) applications that are relevant to coastal studies are being pursued by researchers in a range of Earth science disciplines. Examples include the mapping of "bald earth" land surfaces below even moderately dense vegetation in studies of geologic framework and hydrology, and determination of the vegetation canopy structure, a key variable in mapping wildlife habitats. ALS has also proven to be an excellent method for the regional mapping of geomorphic change along barrier island beaches and other sandy coasts due to storms or long-term sedimentary processes. Coastal scientists are adopting ALS as a basic method in the study of an array of additional coastal topics. ALS can provide useful information in the analysis of shoreline change, the prediction and assessment of landslides along seacliffs and headlands, examination of subsidence causing coastal land loss, and in predicting storm surge and tsunami inundation.

ADDITIONAL INDEX WORDS: *Shoreline change, airborne laser altimetry, LaserMap.*

INTRODUCTION

During the last decade, several complementary airborne remote sensing methods have matured, resulting in significant new capabilities that are enabling advances in coastal research. Topographic information, essential for regional and local geomorphologic studies, and useful in investigations of sedimentary processes, hydrology, pedogenesis, and wildlife habitats, can now be rapidly and accurately acquired at various spatial scales by airborne laser surveying (ALS) (ACKERMANN, 1999; BUFTON, 1989). Airborne laser surveying, or "topographic lidar", is a type of remote sensing generally known as "Light Detection and Ranging" (lidar) that has undergone very rapid development during the last two decades (GARVIN, 1993; FLOOD and GUTELIUS, 1997). Airborne laser surveying herein refers to airborne topographic lidar, exclusive of other lidar methods. Numerous recent studies have demonstrated that current ALS systems have the potential to contribute within a wide range of coastal scientific investigations (CARTER and SHRESTHA, 1997; FLOOD *et al.,* 1997; GUTIERREZ *et al.,* 1998; HUISING and VAESSEN, 1997; KRABILL and SWIFT, 1982; KRABILL *et al.,* 2000; SALLENGER *et al.,* 1999a; SHRESTHA and CARTER, 1998).

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The advent of laser scanning as a new method for the direct, high density measurement of decimeter accuracy elevation from aircraft has been enabled by the parallel development of several incorporated techniques. Kinematic differential Global Positioning System (GPS) methods now enable the positioning of light aircraft to within several centimeters (KRABILL and MARTIN, 1987). Inertial Navigation Systems (INS) or Inertial Measuring Units (IMU) can now provide three-dimensional aircraft orientation at 64-Hz within 0.1 degree, rendering aerotriangulation based on ground data points obsolete (DELOACH, 1998). Modern lightweight laser pulse transmitters can be operated at extremely high repetition rates ranging to greater than 20,000 pulses per second, and can provide ranges from a nominal 1000 m altitude with an accuracy of 1 cm or better (BUFTON, 1989).

Combined within contemporary airborne laser mapping systems, these newly emerged technologies now enable low cost geomorphic surveys at decimeter vertical accuracy and at spatial densities greater than 1 elevation measurement per square meter. Multiple-reflection ALS is uniquely well suited to the mapping of land surfaces below even moderately dense vegetation. This technique enables the creation of "bald earth" digital elevation models in forested areas for application in investigations of geologic structure and hydrology

(Krabill *et al.*, 1984; Kraus and Pfeifer, 1998; Lohr, 1997; Ritchie, 1995). In addition to sub-canopy topography, topographic lidars that capture the entire time-amplitude history of the return pulse can acquire the height and vertical structure of vegetation (Blair *et al.*, 1999). Unlike microwave or passive optical sensors, topographic lidars that capture the full reflected pulse can provide volumetric representations of canopy structure (Blair *et al.*, 1994; Harding *et al.*, 1994; Lefsky *et al.*, 1999).

As much recent work has demonstrated, ALS is an excellent means of mapping change along barrier island beaches and other sandy coasts (Carter and Shrestha, 1997; Flood *et al.*, 1997; Gutierrez *et al.*, 1998; Huising and Vaessen, 1997; Krabill and Swift, 1982; Krabill *et al.*, 2000; Sallenger *et al.*, 1999a; Sallenger *et al.*, 1999b; Sallenger *et al.*, 1999c; Shrestha and Carter, 1998). The ability of ALS to rapidly survey long, narrow strips of terrain is very valuable in this application, as beaches are very elongate, highly dynamic sedimentary environments that undergo seasonal and long-term erosion or accretion, and are also impacted by severe storms (Sallenger *et al.*, 1999b). Closely related applications are airborne laser mapping of flood-prone coastal fluvial zones, and the use of laser bathymeters to survey benthic change driven by hurricanes (Pereira and Wicherson, 1999). Wave effects on nearshore circulation, sediment transport, and littoral zone topography may be investigated through ALS observations of sea state and surface wave displacement over continental shelves (Hwang *et al.*, 1998; Tsai and Gardner, 1982).

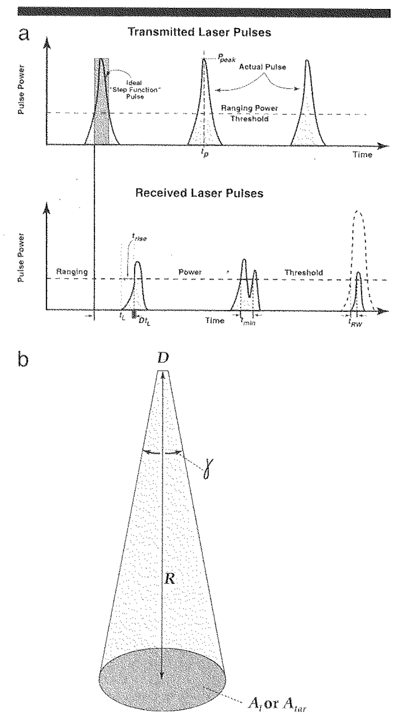

Figure 1a. Relationships between transmitted and received laser pulses (adapted from Wehr and Lohr, 1999).

Figure 1b. Geometry of a single laser shot.

OBJECTIVES

The goal of this paper is to provide an overview of the methods applied within the NASA/USGS/NOAA U.S. "lower 48" coastal mapping project (Sallenger *et al.*, 1999b) for airborne laser surveys of coastal geomorphology. The specific objectives of this paper are:

(1) to provide the basic principles that govern the acquisition of laser ranging observations for surveys of coastal topography, and
(2) to describe the topographic lidar surveying and processing methods in use by a NASA/USGS/NOAA project that has mapped most of the conterminous US coastline.

Basis of Lidar Remote Sensing

The acronym "laser" stands for "*l*ight *a*mplification by *s*timulated *e*mission of *r*adiation" and refers to devices that rely on stimulated emission to generate narrow spectral band radiation, in contrast to conventional broad spectral band spontaneous emission of radiation governed by Planck's Law. The invention of laser transmitters capable of compressing laser energy into very short, high power density single pulses enabled range-resolved measurements (McClung and Hellwarth, 1962), analogous to microwave *radar* ranging. By timing the two-way travel time of a laser pulse reflected off a remote target, the range to the reflector can be directly determined through division by the speed of light. The acronym "lidar" (light detection and ranging), generally refers to any remote sensing system that emits laser light and detects, ranges, or identifies remote objects based on the time-resolved sensing of light reflected or emitted through subsequent fluorescence from that object (Measures, 1984). By definition, lidar is a type of active remote sensing, because it incorporates an energy source to illuminate objects. Therefore, lidar differs fundamentally from passive remote sensing methods, such as multi-spectral scanning or aerial photography that rely upon reflected sunlight.

SUMMARY

Based on its capacity for carefully-timed high resolution regional surveys keyed to natural processes, ALS is becoming a fundamental tool for coastal scientists within coastal studies. This paper provides a set of basic equations that describe laser ranging, and its implementation within the airborne laser scanning of topography. A description of the processing steps used by NASA and the USGS to extract scientifically useful information from the vast number of observations that are obtained through NASA ATM surveys is provided. The multi-tiered lidar processing approach outlined here supports the geometric, reference system, and file structure transformations that are required for most coastal applications of ALS. This approach is being incorporated in a software package called LaserMap that creates lidar data products that may be directly inserted into a Geographic Information System, or used within specialized analysis programs designed to extract landscape information for coastal studies.